Soft-Proton-Exchange Tapers for Low Insertion-Loss $LiNbO_3$ Devices

Davide Castaldini, Paolo Bassi, Sorin Tascu, Pierre Aschieri, Marc P. De Micheli, and Pascal Baldi

***Abstract*—We present the results of an experimental study of waveguide tapers realized in $LiNbO_3$ using the soft-proton-exchange process and the waveguide segmentation technique. Measurements show that they can be favorably introduced between the nonlinear or electrooptic part of the components, which require strong mode confinement to increase efficiency, and the coupling section with a standard optical fiber, which requires low mode confinement in order to have low coupling losses. These tapers allow almost lossless mode-shape transformation. Preliminary results show that they allow reducing the coupling losses by up to 0.7 dB, thus proving the practical interest of the approach.**

***Index Terms*—Integrated optics (IO), optical device fabrication, optical propagation, optical-waveguide components, quantum communication.**

I. Introduction

INSERTION losses have always been a major problem in integrated optics (IO). Reducing the insertion losses is important for telecom and sensor applications and is mandatory in the case of quantum communication where the information is carried by single photons and where amplifiers are not allowed. Losses are due to misalignments, Fresnel reflection, and mode mismatch. Misalignments between fiber and IO device can be avoided using careful aligning procedures. Fresnel-reflection losses, which are due to the different values of the refractive indexes of the IO waveguide and the optical fiber, can be reduced using index matching fluids or antireflection coatings at the end face of the sample. Mode-mismatch losses are due to the different mode sizes in the IO waveguide and the fiber. They are particularly important in the case of active electrooptic or nonlinear (NL) devices where the component efficiency is a growing function of the mode confinement. In these cases, designing the waveguide to optimize its coupling with low confinement telecom single mode fibers is far from being optimum, but it is the more commonly used technique [1] since a practical and cost effective solution allowing longitudinal variation of the transversal section of the waveguide mode is still missing.

This mode-size transformer (taper) should be adiabatic, as short as possible, in order to realize the best tradeoff between the propagation losses and the coupling efficiency. In the literature, a lot of solutions for the design of a taper have been proposed [2]–[5]. Among them, the segmented-waveguide (SWG) configuration is attracting as it does not introduce any additional step in the fabrication process [6]–[11].

In principle, this technique is rather general and can be adapted to any material or waveguide-fabrication technique. Nevertheless, as the excess losses induced by the segmentation depend very much on material and waveguide-fabrication technique, each case has to be carefully studied experimentally. In this paper, we present a study devoted to waveguides realized in Z-cut wafers of $LiNbO_3$ that are commonly used for their good NL properties, allowing, for example, the fabrication of efficient optical frequency converters and photon pair sources required for quantum communication at telecom wavelengths [12].

In order to realize the optical waveguides in this substrate, various techniques have been proposed in the past: outdiffusion [13], titanium diffusion [14], ion implantation [15], proton exchange [16], and its different implementations (simple proton exchange [16], annealed proton exchange [17], and soft proton exchange (SPE) [18]). Among the PE techniques, we choose the SPE process which does not perturb the crystalline structure of $LiNbO_3$ while other ones do [19], [20]. In particular, the ferroelectric domain inversion of the periodically poled lithium niobate (PPLN) devices used for photon pair generation remains intact after SPE [21].

The reported results show that when pushing the SPE parameters to obtain waveguides with the maximum Δn which allows maximum field confinement, tapers that are showing an overall reduction of the insertion losses with respect to the untapered waveguide can be successfully realized. Moreover, these results also demonstrate that, compared to classical tapers, segmented waveguides are not only technologically simpler to fabricate but can also provide larger coupling-loss reduction. Segmentation allows, in fact, to increase independently both the horizontal and the vertical sizes of the integrated optical waveguide mode. One can then easily tailor the mode shape to optimize coupling to any other waveguide.

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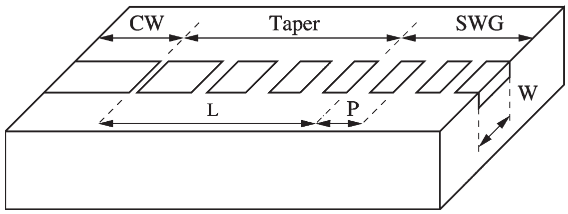

Fig. 1. Schematic of the tested devices.

This paper is organized as follows. In Section II, the waveguide-taper design and fabrication processes are described. In Section III, the different characterization techniques used to evaluate the improvements of the taper are illustrated. In Section IV, the experimental results obtained with different fabrication parameters of the taper are presented, and finally, conclusions are drawn.

II. Device Fabrication

The tested devices are constituted by a taper that transforms the highly confined mode of a continuous waveguide (CWG) to the loosely confined mode of a segmented one, as shown in Fig. 1.

SWG behavior can be described using the so-called equivalent-waveguide theorem for periodic structures [22]–[24]. For wavelengths far away from the band gap, an SWG is equivalent to a CWG with the same depth and same width but with a surface index equal to

$$n_{\mathrm{eq}} = n_{\mathrm{sub}} + \Delta n \cdot \mathrm{DC}$$

where n_{sub} is the substrate index, and DC is the duty cycle defined as the ratio between the length of the high index segment and the period. In the case of a taper, the DC is varying from $\mathrm{DC} = 1$ (CWG) to smaller DC so that the surface index of the equivalent waveguide is reduced as well as the mode confinement. Once the desired mode size is reached, the DC is kept constant down to the end of the sample to stabilize the mode size after the transformation in the taper.

Samples are fabricated on a Z-cut $LiNbO_3$ substrate with the SPE technique. A mixture of lithium benzoate (LB) and benzoic acid constitutes the proton source necessary to increase the extraordinary index of the substrate. Only quasi-TM modes are guided because the ordinary index of the SPE waveguide is not increased. The percentage of LB present in the mixture determines, with the temperature and the exchanged time, the index profile. An increase of the percentage of LB induces a reduction of the proton concentration. Therefore, the index profile of the final structure can be modified by simply controlling the LB percentage.

First of all, we have fabricated some planar waveguides with different percentages of LB with exchanges of 72 h and temperature of 300 °C. Such planar waveguides have been then characterized through the m-lines technique at 632 nm. Fig. 2 shows the value of the effective index of the fundamental mode as a function of the different percentages of LB.

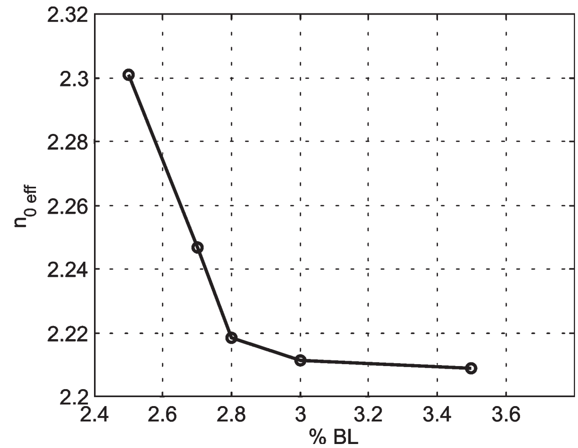

Fig. 2. Effective index of the fundamental mode versus the percentage of LB for SPE planar waveguide, which is deduced from m-lines measurements at 632 nm.

TABLE I
PARAMETERS USED FOR THE TAPERS THAT ARE PRESENT IN THE SAMPLE

P [µm]	DC	W [µm]	L [µm]
15	0.5	5	100
25	0.6	7	600
	0.7		1000
			1400

The high values of the effective index obtained with low percentages of LB are related to the deeply perturbed crystalline structures. For LB percentages larger than the threshold value of 2.8%, the crystalline phase is not modified, and we refer to this regime as the SPE regime.

A 200-nm thick SiO^2 mask patterned by a lift-off process has been used to define the taper, the continuous, and the SWGs.

The SPE has been used with two different values of LB percentage. A first sample has been fabricated with 3.5% of LB, which gives a small index variation, and a second one with 2.8% of LB to create SPE guides with the maximum index variation. In both cases, waveguides are monomode at 1.55 μm, which is the standard telecommunication wavelength and, therefore, the preferred wavelength for long distance quantum communications. The period of the SWG is constant, and the local DC varies from 1 to the desired final DC. The DC variation follows a cubic function along the propagation direction, which allows minimizing the taper losses [6].

The parameters that we can choose when designing the taper are its length (L), the segmentation period (P), the final DC, and the waveguide width (W). Tapers with 48 possible combinations of these parameters were then fabricated on the same substrate. Table I summarizes the values of the parameters that are used for the tapers present on the sample.

The last fabrication step is the end-face polishing to allow end-fire coupling of the sample with the input and output fibers. A particular care is devoted to the control of the angle between the end face and the waveguides which has to be 90° in order to be able to use the Fabry–Pérot technique to measure the propagation losses [25].

III. Experimental Setup

In this section, we describe the experimental setup used to make all the device characterizations. The laser source is a tunable external cavity laser emitting between 1.5–1.6 μm (NetTest Tunics Plus) with an automatic power control system and a narrow linewidth of 150 kHz. In order to control the field polarization state at the entrance of the sample, a monomode polarization maintaining fiber has been used to couple the source and the waveguides. A standard SMF28 has been used to collect the light at the output of the sample. An InGaAs detector allows measuring the light power. The input and output fibers are mounted on the piezoelectric translation stages with 16-nm spatial resolution. All the setups are computer controlled via an IEEE-488 general-purpose interface bus. This system can be used not only to separately evaluate the IO waveguide propagation losses and the mode overlap integral but also their combined effect, comparing the overall coupling efficiencies using the tapered and untapered structures.

The propagation losses are measured using the Fabry–Pérot cavity technique [25]. Measuring the power transmitted through the system at different wavelengths, one obtains fringes whose contrast is directly related to the propagation losses. One of the most important advantages of this technique is that the measurement is independent of the coupling efficiency. We have used this property to avoid parasitic cavities between the sample end faces and the cleaved fibers, simply positioning the fibers at an angle with respect to the waveguide direction.

The overlap integral between waveguide and fiber modes can be evaluated via the measurement of their cross correlation. Such a function is measured by exciting the waveguide under test with a constant power at a fixed wavelength and recording the power collected by the output fiber, while it scans, with 16-nm steps, a 25 $\times$ 25 μm window centered on the waveguide output. Such measurement is similar to that described in [26] and provides many information. First of all, we can quantify the criticality of the fiber-to-waveguide alignment. A sharp cross-correlational function corresponds to a low tolerance to alignment errors, while a smooth cross-correlational function allows some alignment errors without dramatic impact on the coupling losses. Moreover, knowing the cross-correlational function and the fundamental-mode pattern Ψ_{f} of the SFM28 fiber, it is possible to reconstruct the waveguide-mode field distribution Ψ_{w} through a simple deconvolution operation. This finally allows evaluating the intensity overlap integral

$$I = \frac{|\iint \Psi_{\mathrm{w}} \cdot \Psi_{\mathrm{f}}^{*} dS|^2}{\iint |\Psi_{\mathrm{w}}|^2 dS \cdot \iint |\Psi_{\mathrm{f}}|^2 dS}.$$

Evaluating this integral for different tapers allows determining the combination of parameters which gives the better mode matching.

Finally, the overall coupling-efficiency improvement, which depends on the combined effect of taper-induced propagation losses and waveguide-to-fiber mode matching improvement, can be evaluated comparing the maximum power transmitted through the different waveguides present on the sample under test. For each waveguide, the throughput power is measured optimizing contemporarily the positions of both input and output fibers with piezo-controlled stages.

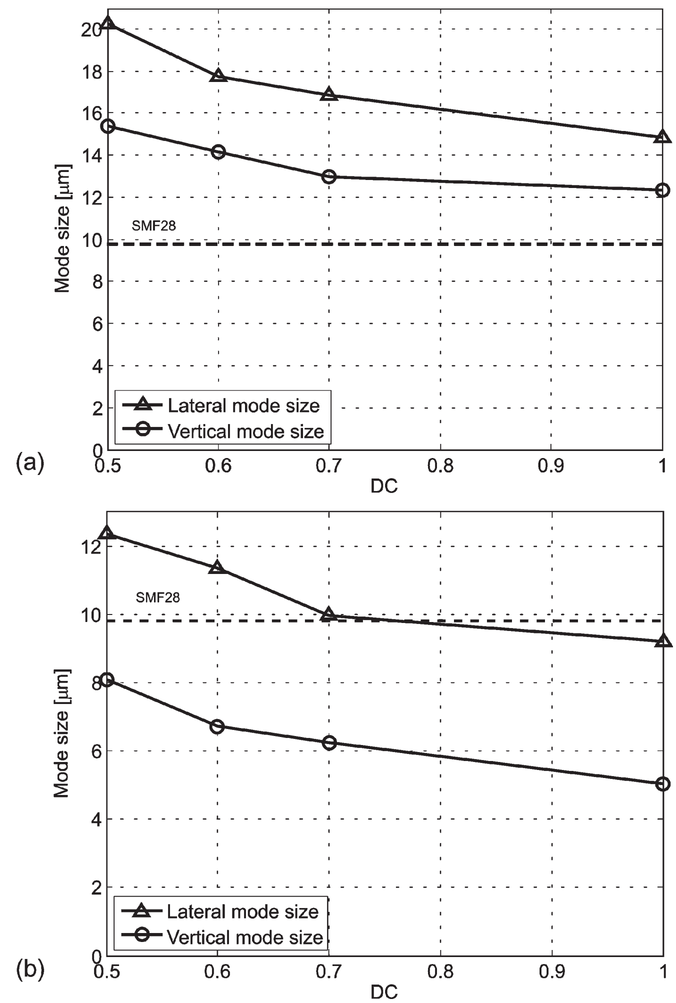

Fig. 3. Measurement of the lateral and vertical mode sizes (at $1/e$ of the field maximum) of SWGs as a function of DC with $W = 5$ μm and $P = 15$ μm for two samples fabricated with (a) 3.5% and (b) 2.8% of LB. The dotted line refers to the mode size of the output fiber SMF28.

IV. Results

We have first characterized the sample obtained with 3.5% of LB. Fig. 3(a) presents the mode size as a function of the DC of the SWGs.

For DC $= 1$, corresponding to a CWG, we found mode sizes bigger than the fiber mode size (dashed line). This indicates that the field is less confined in the waveguide than in the fiber. In this case, we found an overlap of 85%, which cannot be improved by the use of a taper.

The losses measured for the CWG are 1.5 dB/cm. They are mainly caused by surface scattering. After the SPE process, in fact, we have observed the presence of surface irregularities at the edges of the waveguides. The weak confinement of the mode allows a strong interaction with this kind of surface imperfections and is responsible for these rather high scattering losses. In this case, high performances cannot reasonably be obtained for NL or electrooptical components. In fact, even if

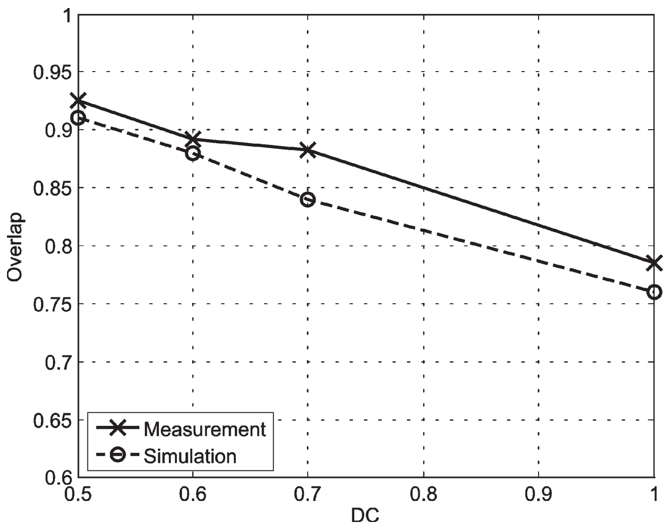

Fig. 4. Overlap between the SWG mode and the SMF28 mode for different DC. (Continuous line with crosses) Measures are compared to (dashed line with circles) the simulation results.

TABLE II
INSERTION LOSSES DIFFERENCE BETWEEN TAPERED AND UNTAPERED WAVEGUIDES FOR THE DIFFERENT FABRICATION PARAMETERS

Period [µm]	Taper length (µm)	DC	$10\log(P_t/P_{CWG})$ [W=5µm]	$10\log(P_t/P_{CWG})$ [W=7µm]
15	1400	0.5	0.78 dB	0.06 dB
	1000	0.6	0.22 dB	-0.25 dB
	600	0.7	0.19 dB	0.20 dB
25	1400	0.5	-0.53 dB	0.37 dB
	1400	0.6	0.15 dB	0.43 dB
	600	0.7	0.51 dB	0.47 dB

coupling losses are small, the weak mode confinement does not allow strong localized field intensity.

The second sample was fabricated performing SPE with 2.8% of LB (see Fig. 2), which is a value corresponding to the maximum index increase achievable with this technique. In this case, a stronger mode confinement is expected. This is confirmed by the results shown in Fig. 3(b), where the mode size of the SWG is reported as a function of the DC. The field is more confined, and this contributes to reduce propagation losses down to 1 dB/cm.

As said before, the drawback of a smaller mode size is the increase of the coupling losses related to the reduction of the mode-fiber overlap. Fig. 4 shows that for DC $= 1$, the overlap is 78%, but the use of a SWG taper can improve it up to 92% for DC $= 0.5$, W $= 5$ μm, and a period $P = 15$ μm (continuous line). This corresponds to an improvement of 0.71 dB in logarithmic scale. This experimental result agrees with the numerical prediction obtained using a 3-D Beam Propagation Method (BPM) [27] (dashed line in Fig. 4) and improves by 0.37 dB, which is the best performance obtained with a taper constituted by an adiabatic reduction of the waveguide width. Numerical predictions show, in fact, that for the classical taper, the overlap can be at most 85%. Moreover, this result can be obtained with final waveguide width equal to 0.8 μm, which is at the limit of a standard photolithography process.

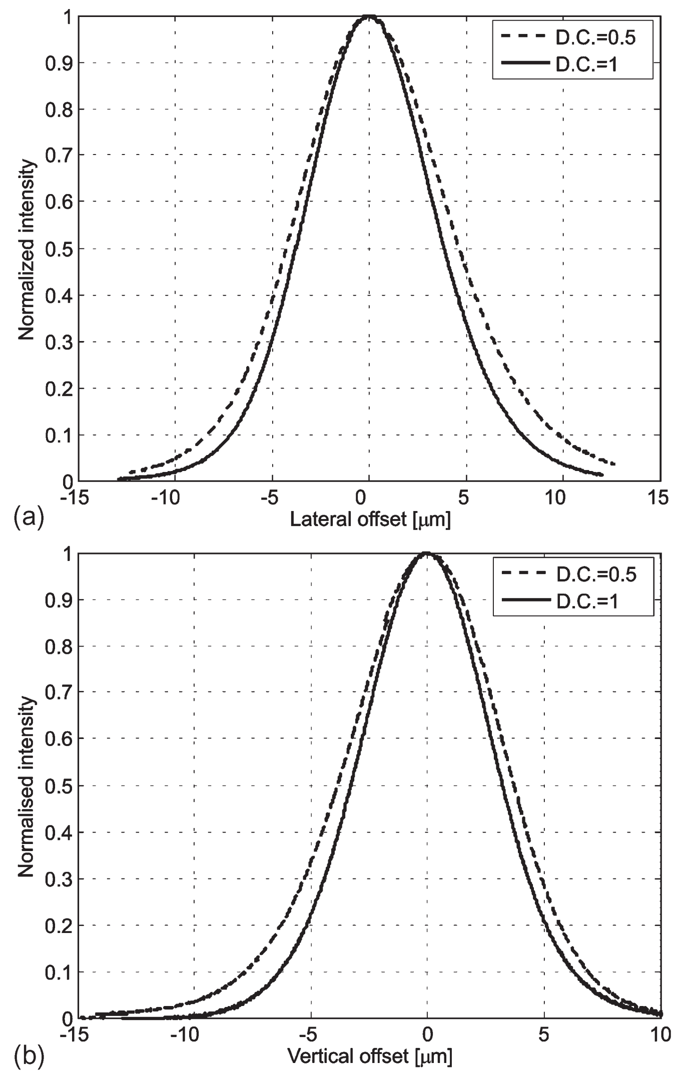

Fig. 5. (a) Lateral and (b) vertical sections of the bidimensional cross-correlational function (continuous line) between SMF28 and CWG and (dashed line) between SMF28 and SWG with $P = 15$ μm, $W = 5$ μm, and DC $= 0.5$.

However, 0.71 dB is not the real performance improvement, which can be obtained using tapered and SWGs, as they induce extrapropagation losses which are not taken into account in the overlap integral. These extra propagation losses are due to imperfect mode transformation and scattering losses at the segments edges. So, the use of a SWG taper becomes effective if the mode matching improvement is larger than the propagation loss increase. Using the Fabry–Pérot cavity technique, which is illustrated in the previous section, taper and SWG introduction were found to cause a loss increase of only 0.04 dB with respect to the CWG. The total improvement obtained in terms of waveguide-to-fiber coupling is then $0.71 - 0.04 = 0.67$ dB. The precision of this result is estimated to be around ± 0.2 dB.

The overall improvement was also measured using the third approach described at the end of Section III. The results are reported in Table II, where P_{t} and P_{CWG} are output powers measured at the end of the waveguides with and without taper, respectively. Negative results correspond to the cases where the overlap improvement does not even compensate for the additional losses. The optimal length of the taper depends on the segmentation parameters, and Table II reports the results for the lengths that provide the best performances. We obtained the overall best result with a 1400-μm long taper associated to a 2600-μm long SWG, with $P = 15$ μm, $\mathrm{W} = 5$ μm, and $\mathrm{DC} = 0.5$. In that case, an overall increase of 0.78 dB of the transmitted power was observed with respect to the CWG. The precision of this measurement is around ± 0.1 dB.

These two different measurements give results, which, taking into account the uncertainties, are equal and confirm the practical interest of SWG tapers realized using the SPE process.

It is worth noting that the test structures realized for this paper have taper at one end only. Therefore, the benefit for a real component with a taper at both ends will be doubled. Further improvement can also be obtained working on the taper length, which can be reduced by reducing the segmentation period.

Besides the reduction of the insertion losses, the use of SWG tapers offers the advantage of a wider cross-correlational function with the mode fiber. Fig. 5 shows the sections of the measured bidimensional cross-correlational function (continuous line) between SMF28 and CWG and (dashed line) between SMF28 and SWG with $\mathrm{DC} = 0.5$ and $\mathrm{W} = 5$ μm. The resolution of these measurements is 16 nm and is limited by the piezoelectric positioning system that we used. A wider cross-correlational function is the signature of a less critical alignment, which is important for industrial applications as it relaxes the constraints on the fiber pigtailing process and, therefore, its cost.

V. Conclusion

In this paper, we have presented experimental results obtained at telecom wavelengths with SWG tapers fabricated in $LiNbO_3$ by the SPE process. We have found that when one uses the SPE parameters necessary to reach the maximum confinement of the guided mode preserving NL and electro-optical coefficients, the introduction of an adapted taper allows reducing by 0.7 dB of the coupling losses with a fiber. This result improves by 0.37 dB, which is the best performance that one can expect to obtain using a conventional taper. For a complete device, presenting optimized tapers at input and output, the benefit could then reach 1.5 dB.

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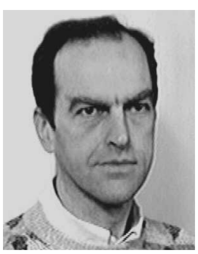

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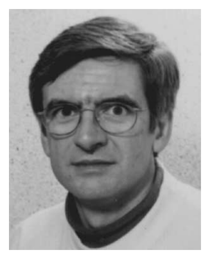
Sorin Tascu was born in Comanesti, Romania, in 1976. He received the B.Sc. degree in engineering physics from Alexandru Ioan Cuza University, Iasi, Romania, in 1999, and the M.S. and Ph.D. degrees from Claude Bernard Lyon University, Lyon, France, in 2000 and 2003, respectively. During his Ph.D., he worked on the study of guided waves, photorefractive phenomena, and luminescence in planar and channel waveguides by using the scanning near-field optical microscopy (SNOM) technique.

From 2003 to 2004, he was a Temporary Teacher and a Research Associate at the Claude Bernard Lyon University, with a research activity on characterization of integrated optics circuits by using SNOM techniques. From 2004 to 2006, he has been holding a postdoctoral position in the Laboratoire de Physique de la Matière Condensée, University of Nice—Sophia Antipolis, France. In 2006, he joined, the Moduloptic S.A., as an R&D Project Leader, which is a start-up aiming at fabricating active integrated-optic components based on lithium niobate. He has published over 11 scientific papers on these subjects and presented over 22 conferences. His research activities concerned the fabrication and characterization of heralded single-photon sources for quantum communications by using parametric fluorescence in waveguides fabricated by soft proton exchange on periodically poled-lithium-niobate substrates. More generally, his research interest was in nonlinear integrated optics and integrated quantum optics.

Pierre Aschieri received the Master's degree in computer sciences from Ecole Supérieure en Sciences Informatiques, Sophia-Antipolis, France, in 1993, the Master's degree in physics in the optics specialty from Ecole Nationale Supérieure de Physique de Marseille, Marseille, France, in 1995, and the Ph.D. degree from the University of Nice—Sophia Antipolis, Nice, France, in 1999, for a numerical and experimental study of optical segmented waveguides.

He has spent training periods to work on numerical modeling optical problems at the Dipartimento di Elettronica, Informatica e Sistemistica, University of Bologna, Bologna, Italy, and at the Indian Institute of Technology, Delhi, India. Since 2000, he has been an Assistant Professor in the Electronics Department, University of Nice—Sophia Antipolis, where he is teaching optical telecommunication and numerical modeling. His research activities concern the modeling of optical waves propagation in periodic linear or nonlinear media. He has studied the losses behavior and the modal properties of periodically segmented waveguides used as modes filters or modes tapers in integrated optics. He is currently involved in wave chaos in periodic waveguides. He has published over 20 scientific papers on these subjects.

Dr. Aschieri is a member of the Société Française d'Optique.



Marc P. De Micheli received the Ph.D. degree and the "Habilitation à diriger les recherches" degree from the University of Nice—Sophia Antipolis, Nice, France, in 1982 and 1991, respectively.

From 1982 to 1984, he had an engineer position at the Fraunhofer Institut für Physikalische Meβtechnik, Freiburg, Germany. Since 1984, he has been at the Centre National de la Recherche Scientifique, Paris, France, and Laboratoire de Physique de la Matière Condensée, University of Nice—Sophia Antipolis, where he worked in integrated optics on $LiNbO_3$ designing, fabricating, and characterizing different components realized using the proton-exchange technique. The progress he achieved in the comprehension and the control of this fabrication process allowed him to successfully participate to the realization of continuous wave, mode-locked, and Q-switched integrated lasers in neodymium-doped $LiNbO_3$. Since 1990, he has been working on waveguide fabrication in periodically poled crystals to achieve phase matching condition at room temperature. He has demonstrated parametric fluorescence with a great efficiency, and his present goal is the realization of an integrated optical parametric oscillator (OPO), integrated sources adapted to quantum optics, and all-optical modulators using cascading of χ^2 processes. From 2001 to 2005, he has participated to the creation of Moduloptic, which is a start-up aiming at fabricating active integrated-optic components based on lithium niobate. Recently, he created a new research team in order to extend his nonlinear-optic activities to semiconductors and more specifically to GaN. He has published over 70 scientific papers on these subjects and presented over 140 communications in various conferences.

Dr. De Micheli is a member of the Société Française d'Optique, the European Optical Society, and the Optical Society of America.

Pascal Baldi received the Ph.D. degree in physics from the University of Nice—Sophia Antipolis, Nice, France, in 1994.

He was with the Laboratoire de Physique de la Matière Condensée, University of Nice—Sophia, in 1996, where he is currently a Professor in physics, leading the Guided-Wave Optics group. His current main research interests are in quasi-phase-matched nonlinear integrated optics and integrated quantum optics. He has published over 50 scientific papers and presented over 70 communications in various conferences.

Dr. Baldi is a member of the program committee of several conferences on nonlinear and integrated optics. He is a referee for IEEE, the Institution of Electrical Engineers (IEE), the Optical Society of America, and the European Physical Society. He is in charge of regional, national, and international fundings. In 1995, he was the recipient of a Lavoisier Fellowship from the French Ministry of Foreign Affairs for postdoctoral research at the Center for Research and Education in Optics and Lasers, University of Central Florida, Orlando.